Exploitation of Thermal Signals in Tidal Flat Environments

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LONG-TERM GOALS

The overall goal is to identify and understand the physical processes that shape and change coastal environments. Emphasis is on the application of remotely sensed infrared signals that can be compared with in situ observations and assimilated within predictive models. In tidal flat environments, major goals are detection of: geotechnical properties (e.g., sediment strength), morphologic features (e.g., channels), related hydrodynamic events (e.g., plumes).

OBJECTIVES

The primary objective of these joint efforts is to develop thermal methods for improved monitoring and prediction of tidal flat environments. Specific objectives are to:

- Develop an integrated system for in situ and remote (infrared) measurements of thermal signals in the field, including airborne and fixed platforms,
- Test and apply the Lovell [1985] hypothesis for the porosity of sediment as a function of thermal conductivity,
- Refine methods to estimate inter-tidal bathymetry using sequential waterline detection, and
- Detect and quantify the importance of channel networks.

APPROACH

The technical approach is to conduct field experiments using simultaneous remote and in situ observations of thermal signals in tidal flat environments (Figure 1). Infrared images collected from airborne and fixed platforms are being used to study surface temperatures, which are then related to an array of interior (sediment and water) temperature measurements. The experiments are designed to study geotechnical, hydrodynamic, and morphologic aspects of tidal flats.

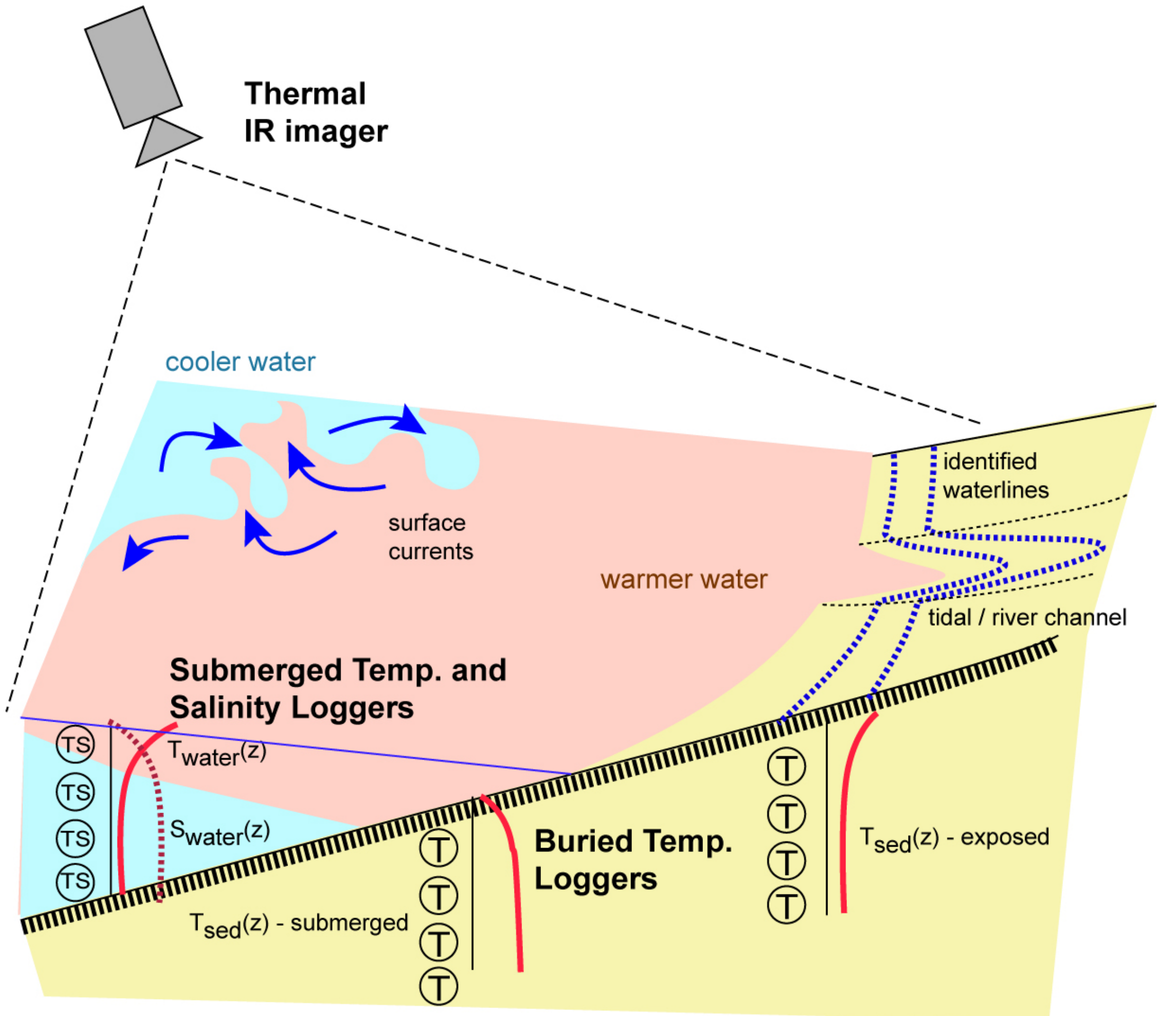

Figure 1. Schematic diagram showing infrared and in situ measurements of thermal signals in a tidal flat environment. The infrared measurements of surface temperature are made from a tower, aircraft, or helikite, and the in situ measurements of interior (both water and sediment) temperature are made from anchored platforms.

The sediment temperature data is analyzed using Lovell's [1985] empirical formula for the fractional porosity *n* (i.e., the water content) of saturated sediments as a function of thermal conductivity *k*, where

$$k = k_s^{(1-n)} k_f^{(n)},$$

and k_s, k_f refer to the thermal conductivities of the solid and fluid, respectively. Assuming a 1D heat balance, the temperature *T* at the surface of the sediment (measured using infrared imagery, see Figure 1) diffuses downward in a vertical *z* profile (measured using buried loggers) at a time *t* rate governed by

$$d^2T/dz^2 = (c\rho/k)\ dT/dt,$$

where *k* is the thermal conductivity of interest, *c* is the specific heat, and ρ is the density [*Subramaniam and Frisk*, 1992; *Jackson and Richardson*, 2002]. Sediment porosity *n* is estimated by finding the best-fit *k* at each location in the imagery and then is compared with sediment samples.

Differential sediment and water surface temperatures are used to detect waterlines and thereby estimate bathymetry. Waterlines extracted within plan-view infrared images at incremental tide stages will be interpolated to a Digital Elevation Model (DEM), similar to work with optical imagery in the nearshore [*Plant and Holman*, 1997] and infrared satellite imagery [*Ryu et al*., 2002]. Infrared imagery is well suited to shoreline identification due to the differential heating rate of sediment (fast) versus water (slow). We have increased the likelihood for quality data return and the general image resolution over satellite imagery by developing and deploying a small aircraft based thermal imaging system. Flying over the flats in a "lawn-mowing" fashion, we later georectify and mosaic the collected imagery for quantitative analysis. Bathymetry estimates will be compared against ground surveys collected during the pilot experiment.

The field data were used to quantify bulk surface fluid masses and their change in position over time (i.e velocity using imagery [e.g. *Holland et al.*, 2001]) and estimate volume transport (using in situ data [*Wunch*, 1996]). These hydrodynamic quantities will be used to evaluate correlations with bathymetric features, such as channels, and will be compared with in situ velocity measurements.

WORK COMPLETED

During FY08, we developed and test tower and airborne imaging systems for remote locations. We successfully deployed these and other insturments in pilot field experiments on the Skagit and Willapa Flats of Washington State. In addition to the primary measurements of temperature and pressure, a metreological station and two accoustic Doppler current profilers were successfully deployed. The data set includes a range of conditions and spans the transition from diurnal to semi-diurnal tides.

In FY09, we processed data from the summer 2008 field experiments. We successfully completed additional field experiments on the Skagit and Willapa Flats of Washington. The infrared measurements were made from a small plane (Cessna 172) and a "helikite" platfrom. The in situ measurements included arrays of temperature and pressure, as well as a metreological station and two accoustic Doppler current profilers. Instruments were successfully maintained from May to September 2009. In addition, long term measurements (monthly survey flights and in situ temperature measurements) continued thoroughout FY09.

During the first part of FY10, we processed data from the summer 2009 field experiments, and then presented our results at a Tidal Flats DRI meeting in October 2010 and the Ocean Sciences meeting in February 2010. During the second part of FY10, we successfully completed additional field experiments on the Willapa Flats of Washington State, as shown in Figure 2. Infrared and LIDAR measurements were made from a tower at the "D" chanel of Willapa Bay. The in situ measurements included arrays of temperature and pressure, as well as a metreological station and two accoustic Doppler current profilers. The LIDAR was provided by S. Elgar & B. Raubenheimer (WHOI). Figure 2 shows the tower and the boat used for data collection during a one-week focus study in March 2010. In addition, longer term time-lapse images were collected from

December 2009 to March 2010 and meteorlogical measurements continued until September 2010.

***Figure 2. Example of field data collection on the Willapa Flats, using a tower afixed to an existing piling.* (Photo taken at high tide.)**

RESULTS

Results to date confirm that thermal signals can be used to remotely classify sediments and detect bathymetric features. In particular, the heat flux of exposed sediments is related to the composition and porosity of sediments (Thomson, 2010). Sediments absorb heat during periods of strong solar radiation consistent with a 1D diffusion equation (Kim et al., 2007). As detailed in new a publication this year, an empirical model for diffusivity as a function of porosity (Lovell, 1985) successfully explains observations. The sandy sediments have a much stronger response to heating, because the water content and porosity is lower, compared with the muddy sediments. Figure 4 shows a preliminary application to airborne infrared sensing in Willapa Bay.

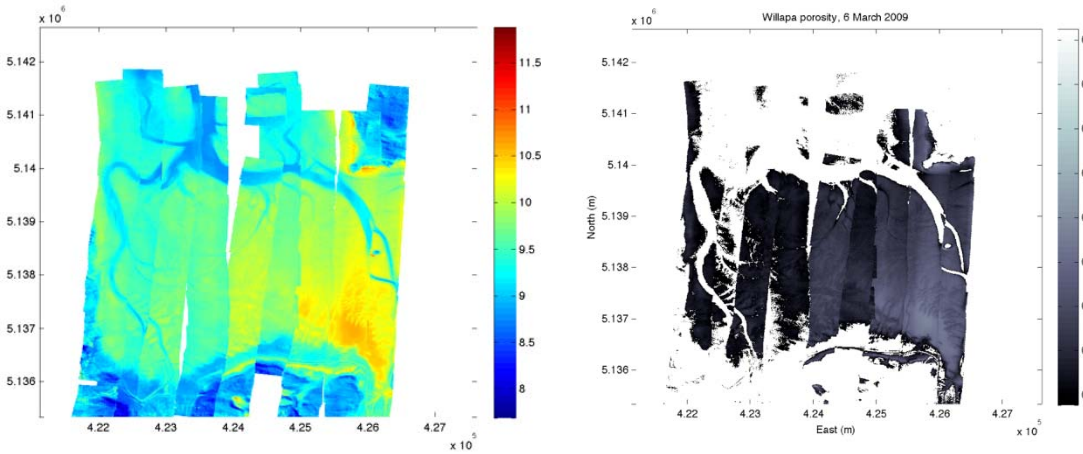

Figure 4. Aerial infrared map (left) and inferred porosity of exposed sediments (right) from Willapa Bay.

Thermal images collected from overflights showed substantial gradients, which can be exploited to measure large-scale bathymetry and circulation. A first-time bathymetry map was calculated from a composite set of airborne thermal imagery between April and July in 2009. A maximum-gradient and threshold based method was devised to detect sharp transitions between temperature regions with accompanied significant temperature change (Figure 5, left). Thus, the method is skilled in selecting the distinct temperature difference between heated exposed sediments and cooler surface water (as is typical in the summer) as opposed to the less defined mixing region of warm and cool surface waters that can be present on the flooding tide (which would have been erroneously detected by a simple threshold method alone). A bathymetric map of the intertidal region is calculated from a set of shorelines at different tidal water levels made over successive flights (Figure 5, right). The appearance of the resulting map is encouraging, though the full map is noisy due to interpolation and smoothing of small-scale channel morphology.

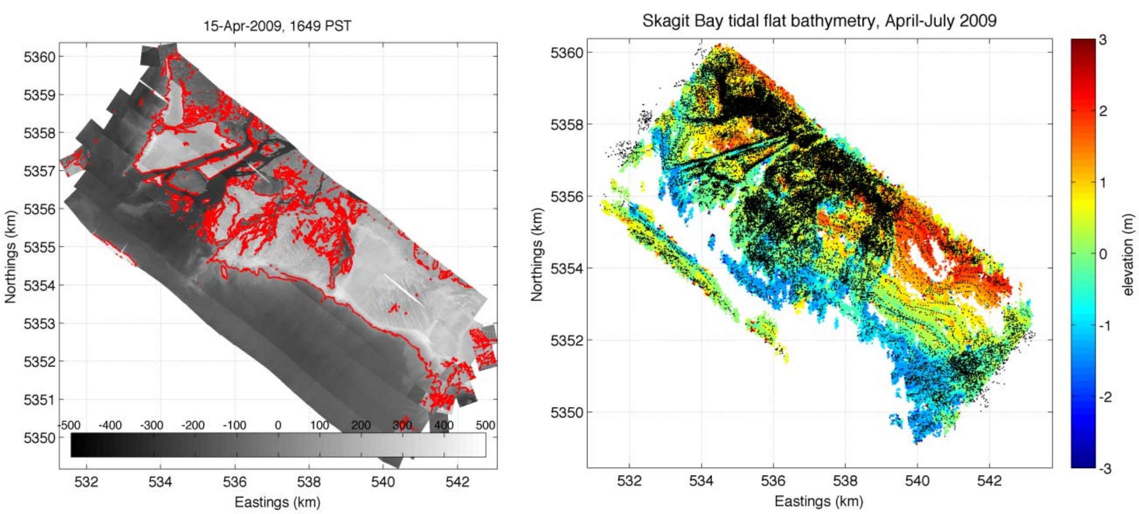

Figure 5. Aerial infrared map (left) from Skagit bay with an automatically identified waterline (red). A composite map interpolated from successive shorelines is shown on

the right. Black dots indicate locations of identified shorelines and highlight channel locations.

Waterlines bounding tidal flat channels were also examined for morphological change. Figure 6 shows a single year cycle of waterlines in geo-referenced infrared images on the upper Skagit flats near Craft Island detected from the automated routine. The automatically identified distributary channels appear to show dramatic change over the year, yet are also spatially confined. Increased river flow during storm and melt water run-off (April-June) appears to be accommodated by channel development to the east of the main north-south aligned channels. River water then reoccupies the main channels during low flow in summer and early fall flow periods. The main low flow channels have surprising little change in channel patterns and location from fall 2008 and summer 2009. This could be due to a variety of conditions including larger-scale bathymetry, partitioning of flow through the vegetated marsh, and sediment composition and strength among others.

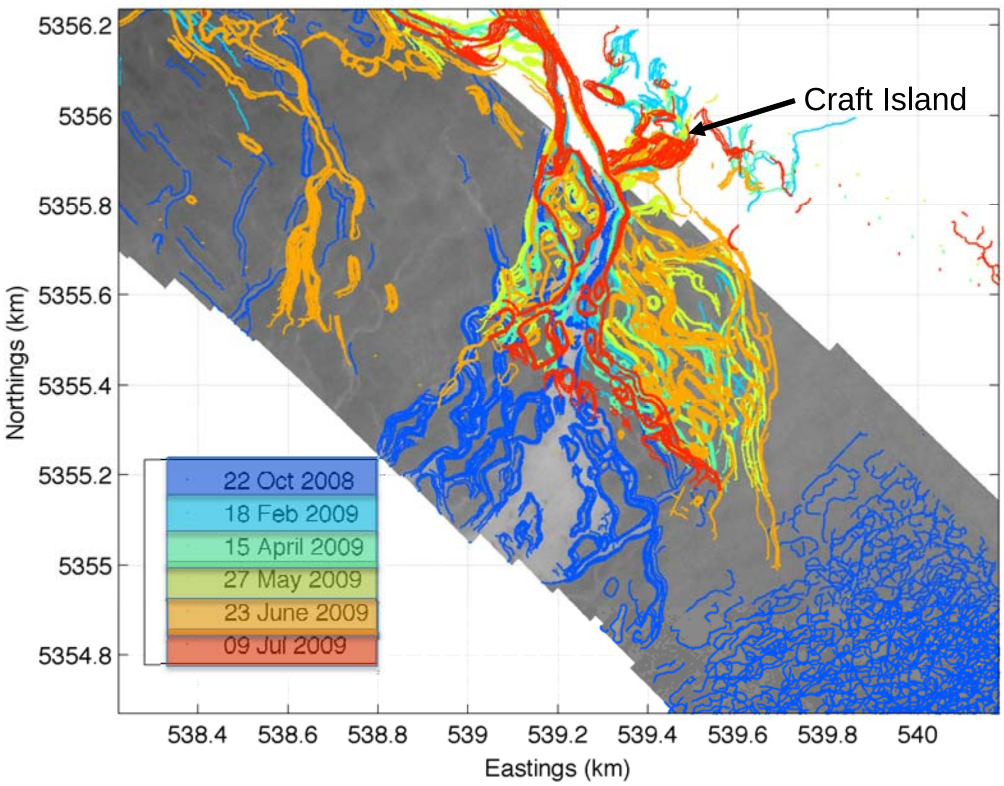

Figure 6. Waterlines detected in an annual sequential of airborne infrared images of the distributary channels on the Skagit flats near Craft Island. The base image os a thermal map from

IMPACT/APPLICATIONS

Improving techniques to remotely quantify tidal flat properties will allow for real time monitoring and safe operation in these environments. In particular, remote porosity

estimation, bathymetry mapping, and channel detection will improve navigation for amphibious landings.

RELATED PROJECTS

A new LTAIR (Lighter Tan Air InfraRed) imaging platform, developed under a DURIP (PI: Andrew Jessup), has dramatically improved spatial coverage of our infrared sensing by providing additional elevation and dwell time.

An ongoing MURI (Coherent Structures in Rivers and Estuaries Experiment, PI: Andrew Jessup) has provided infrared image data for proof of concept applications in the remote sensing of tidal flats (www.cohstrex.apl.washington.edu). Equipment and resources are shared with this project.

A new DoD MURI (Data Assimilative Modeling and Remote Sensing for Littoral Application, PI: Andrew Jessup) will benefit from experience gained here and use many of the techniques and equipment tested in these sets of experiments.

This effort is a contribution to the Tidal Flats DRI (www.tidalflats.org).

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14. ABSTRACT
Infrared images were collected from airborne and fixed platforms over the Skagit Bay and Willapa Bay tidal flats in western Washington State. Differential sediment and water surface temperatures are used to detect waterlines using a newly developed automated routine for airborne IR imagery. Sequential mapping of waterlines over tidal changes is used to build an estimate of intertidal bathymetry. A 50 square kilometer map was constructed from airborne flights over Skagit Bay. Tidal flat channel morphodynamics was also quantified from monthly airborne mapping, and suggests strong coupling between channel density and seasonal river outflow. Remote sensing thermography is used to study and interpret surface sediment and water temperatures, which are then related to an array of interior temperature measurements. In situ temperature data were used to confirm that vertical heat flux is a predictable function of sediment porosity and suggests that thermal signals can be used to remotely classify sediments. Future work will focus on improving bathymetric mapping and estimating shallow water flow and exfiltration from tidal mud flats.

15. SUBJECT TERMS
tidal flats, infrared remote sensing, sediment porosity, bathymetry

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